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Effect of sand-fixing vegetation on the hydrological regulation function of sand dunes and its practical significance

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Abstract: Soil water content is a key controlling factor for vegetation restoration in sand dunes. The deep seepage and lateral migration of water in dunes affect the recharge process of deep soil water and groundwater in sand dune ecosystems. To determine the influence of vegetation on the hydrological regulation function of sand dunes, we examined the deep seepage and lateral migration of dune water with different vegetation coverages during the growing season in the Horqin Sandy Land, China. The results showed that the deep seepage and lateral migration of water decreased with the increase in vegetation coverage on the dunes. The accumulated deep seepage water of mobile dunes (vegetation coverage<5%) and dunes with vegetation coverage of 18.03%, 27.12%, and 50.65% accounted for 56.53%, 51.82%, 18.98%, and 0.26%, respectively, of the rainfall in the same period. The accumulated lateral migration of water in these dunes accounted for 12.39%, 6.33%, 2.23%, and 7.61% of the rainfall in the same period. The direction and position of the dune slope affected the soil water deep seepage and lateral migration process. The amounts of deep seepage and lateral migration of water on the windward slope were lower than those on the leeward slope. The amounts of deep seepage and lateral migration of water showed a decreasing trend from the bottom to the middle and to the top of the dune slope. According to the above results, during the construction of sand-control projects in sandy regions, we suggest that a certain area of mobile dunes (>13.75%) should be retained as a water resource reservoir to maintain the water balance of artificial fixed dune ecosystems. These findings provide reliable evidence for the accurate assessment of water resources within the sand dune ecosystem and guide the construction of desertification control projects.

Keywords: vegetation coverage; hydrological regulation; soil water deep seepage; sand dune; water balance; desertification control

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1 Introduction

Water is the main restricting factor that influences the growth of plants. Soil moisture is essential for plant colonization and growth, and plants also have a significant influence on soil moisture dynamics (Li et al., 2009; Yang et al., 2014; Dai et al., 2015). Especially in arid and semi-arid sandy areas, the relationship between soil moisture and vegetation is stronger, and the influence of vegetation on soil moisture is more obvious (Alamusa et al., 2005; Wu et al., 2016). Soil moisture is

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an important limiting factor for plant survival in dune ecosystems. Soil moisture determines the process of seed germination and seedling settlement, affects the process of plant growth, and restricts the distribution pattern of plants (Alamusa et al., 2005; Wang et al., 2008). At the same time, sand-fixing plants also produce a variety of feedback effects on soil moisture. For example, sand-fixing plants reduced the soil moisture content and changed the spatial distribution pattern and temporal variation characteristics of soil moisture (Li et al., 2001; Liu et al., 2009).

The method of desertification control by establishing artificial vegetation on mobile dunes has been widely used in China since the 1950s. Although remarkable sand-control effects have been achieved, this method has a negative impact on the water balance at the scale of the sand dune ecosystem (Li et al., 2013). In the process of establishing artificial vegetation to transform mobile dunes into fixed dunes, the sand-fixing vegetation changed the original water circulation process (Alamusa et al., 2005), resulting in an obvious decreasing trend of soil moisture in the dunes. Such large-scale sand-fixing vegetation construction is the main reason for water loss in dune ecosystems (Li et al., 2007; Hua et al., 2012), which weakened the hydrological links between dunes and other surrounding ecosystems (such as the low-lying wetlands between dunes).

Previous studies have found that the soil water content of mobile dunes can usually be maintained between 3.00% and 5.00%, while that of fixed dunes is usually between 1.50% and 3.00% (Alamusa et al., 2005). Compared with fixed dunes, more water can be stored in mobile dunes, which can export more water to the external environment than fixed dunes (Yang et al., 2014; Yao et al., 2017). The storage water of mobile dunes can replenish deep soil water, groundwater, and surrounding inter-dune land through deep seepage and lateral migration processes, maintaining a high water supply in the whole sand dune ecosystem (Li et al., 2009; Liu et al., 2009; Zhou et al., 2009). Therefore, mobile dunes can be regarded as a reservoir for water resources in sand dune ecosystems.

The vegetation coverage on the dunes controls the dune's hydrological regulation capacity. In general, the soil moisture condition gradually deteriorates during the transition from a mobile dune to a fixed dune by establishing vegetation with high coverage (Yang et al., 2014). Alamusa et al. (2004) found that the growing age and planting density of sand-fixing vegetation affected the soil water content of the dunes in the Horqin Sandy Land. The soil water content significantly decreased with the increases in the age and density of sand-fixing vegetation, from 3.20% for a 4-year fixed dune to 1.90% for a 19-year fixed dune, and from 2.30% under a 2 m×2 m density to 1.20% under a 1.0 m×0.5 m density. Li et al. (2009) also found that with the establishment of sand-fixing vegetation, the soil moisture content showed a decreasing trend in sand dunes. When the sand-fixing vegetation was established 10 a later, the soil water content of the dunes decreased from 3.50%–3.80% at the initial stage of vegetation establishment to about 2.00%, and 15 a later, the soil water content of the dune was close to 1.00% (Li et al., 2001). Sand-fixing vegetation reduced soil moisture in sand dunes, which then affected the process of soil water seepage. When the vegetation coverage of the dunes was greater than 45.00%, the deep seepage water did not exceed 2.00% of the rainfall during the same period (Feng et al., 2015). The method of large-scale construction of vegetation with high coverage would significantly reduce the soil water stored, thereby gradually reducing the external water supply capacity of the dune (Wang et al., 2008; Liu et al., 2011), which would affect the water balance and vegetation stability of the sand dune ecosystem.

The influence of vegetation on the soil water seepage process has been widely recognized (Feng et al., 2015; Li et al., 2015; Duan et al., 2016; Yao et al., 2017), but quantitative studies on the effect of vegetation on soil water seepage are rare. It is urgent to clarify the influence of vegetation coverage on deep seepage. In this context, we applied self-made observation instruments to measure the deep seepage and lateral migration of dune water under different vegetation coverages in the Horqin Sandy Land, China. We clarified the quantitative and temporal distribution characteristics of deep seepage and lateral migration of dune water, and analyzed the influence of vegetation on the processes of soil water seepage and lateral migration. The results will provide a theoretical basis and data support for further clarifying the hydrological regulation function of the dunes.

2 Materials and methods

2.1 Study area

The study area is located in the west of the Horqin Sandy Land, Inner Mongolia Autonomous Region, which is a typical area for desertification control in China (Fig. 1). The area has a typical temperate continental monsoon climate with uneven distribution of annual precipitation. The average annual precipitation is 311.62 mm. On average, more than 70% of the annual precipitation occurs between June and August, while precipitation in spring (March–May) only accounts for 10% of the annual precipitation. The average evaporation is 5.33 (±0.79) mm/d. The annual mean wind speed is 3.17 m/s, the annual mean temperature is 7.03°C, and the frost-free period is 140 d. In the study area, the dunes are undulating and alternate with the inter-dune lowlands, representing a typical sand dune landscape. The main habitat types are mobile dunes, semi-mobile dunes, semi-fixed dunes, fixed dunes, inter-dune lowlands, and sand-covered low hills. The main soil types are aeolian sandy soil, meadow soil, and saline-alkali soil.

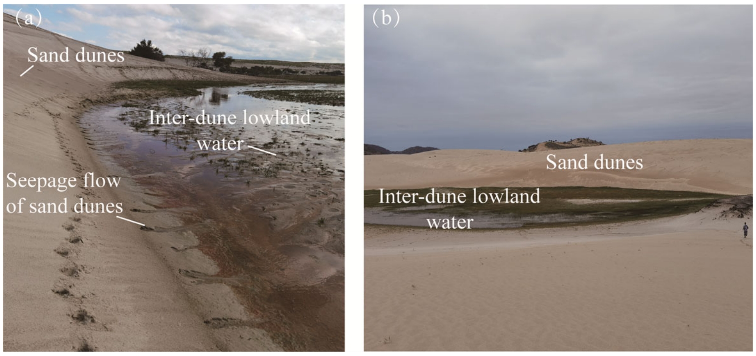

Fig. 1 A scene of mobile dunes supplying water to the inter-dune lowlands. (a), seepage water from mobile dunes recharging inter-dune lowlands; (b), inter-dune lowland water between mobile dunes.

2.2 Experimental methodology

Within a radius of 5 km, one mobile dune, two semi-fixed dunes, and one fixed dune were selected as research objects in the Horqin Sandy Land. Vegetation coverage was measured by the square sample method. From the bottom of the windward slope to the bottom of the leeward slope, three belt transects with an interval of 30 m were set on the surface of each dune. Quadrats of 2 m×2 m were set up on each belt transect at an interval of 10 m, and the canopy width of plants in the quadrats was measured. Vegetation coverage was obtained by the proportion of the ground projection area of the canopy to the overall area of the quadrat. The information on the four experimental sample sites is shown in Table 1.

Table 1 Basic information of the study sites

Sand dune type	Vegetation coverage (%)	Species composition
Mobile dunes	<5.00	*Corispermum candelabrum* Iljin., *Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze, *Artemisia wudanica* (Liou & W. Wang.)
Semi-fixed dunes	18.03 27.12	*Caragana microphylla* Lam, *Artemisia wudanica* (Liou & W. Wang.), *Setaria viridis* (L) Beauv, *Corispermum candelabrum* Iljin.
Fixed dunes	50.65	*Caragana microphylla* Lam, *Artemisia halodendron* Turcz.et Bess., *Leymus chinensis* (Trin.) Tzvel., *Polygonum divaricatum* L., *Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze, *Setaria viridis* (L) Beauv

To obtain deep seepage and lateral migration of water information on the sand dunes, we designed two kinds of infiltration water collection devices (Fig. 2). The devices were made of iron plates and iron pipes. There were two types of devices: one was equipped with a water-blocking plate and the other with a non-water-blocking plate (Fig. 2a). A 110-cm-high plate

(the cross-section was shaped as a "U") of the water-blocking plate device can prevent and collect both deep seepage and the lateral migration flow of the dunes. When the device was buried on the dune slope, the opening direction pointed toward the up-slope direction (Fig. 2c), and was thus able to collect both deep seepage and lateral migration of water along with the dune slope. This collected water is represented by A. The non-water-blocking plate device could only collect the deep seepage infiltration water of the dunes, and this collected water is represented by B, so the amount of lateral migration of water of the dunes should be A minus B.

Experimental observation devices were buried in five positions on each experimental sand dune with different vegetation coverages: the bottom of the windward slope, the middle of the windward slope, the top of the slope, the middle of the leeward slope, and the bottom of the leeward slope (Fig. 2b). Each observation site was equipped with three pairs of observation devices, and the spacing within pairs of devices was 25 cm, and the distance between pairs was 50 cm (Fig. 2c). Each pair of observation devices includes a non-water-blocking plate device and a water-blocking plate device arranged in parallel (Fig. 2c). We buried the devices in the observation sites and filled with soil according to the original soil layers. The devices were then left standing for one year after installation before commencing the test, to allow the physical properties of soil in the devices to settle as close as possible to the original soil conditions.

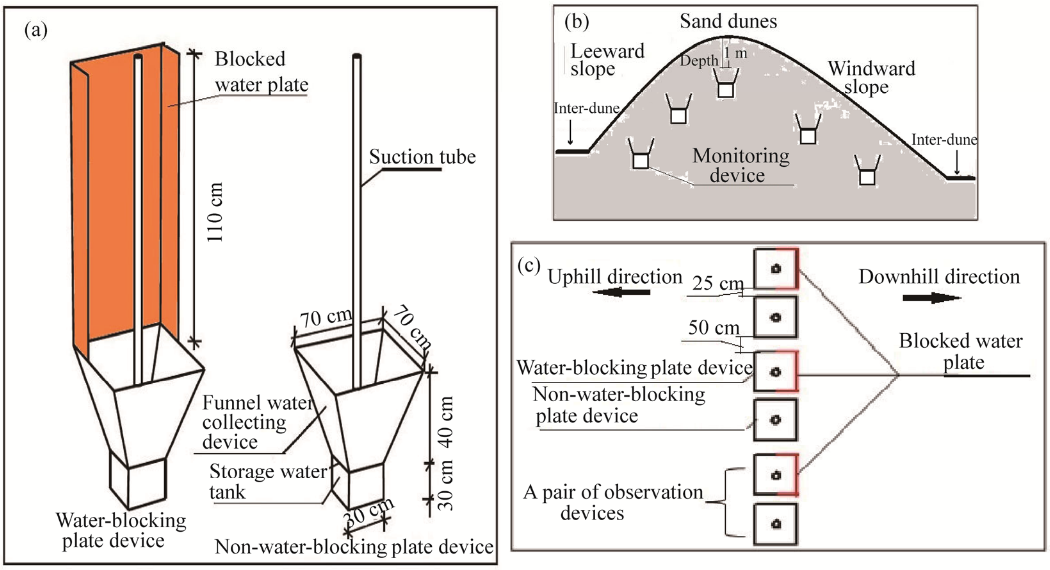

Fig. 2 Schematic diagram of the installation of devices for monitoring deep seepage and lateral migration of soil water. (a), devices for monitoring the deep seepage and lateral migration of soil water; (b), installation location of monitoring devices in sand dunes; (c), installation position of devices at the monitoring site.

The measurements were collected once every 10 d from May to October 2017. The collected water in each device was extracted with a mini self-priming direct current pump from the suction tube in the devices, and then the water was measured with a measuring cylinder. At the same time, automatic rain gauges (DJ-100, Dianjiang Tech Ltd., Chongqing, China) were installed at each observation site to observe rainfall in real time. Statistical analyses were performed with Microsoft Excel 2013 and SPSS v.18.0, and Origin v.8.5 software was used for drawing. Spearman's rank correlation was used to analyze the correlation between rainfall and the amount of deep seepage and lateral migration.

3 Results

3.1 Rainfall characteristics during the experiment

From May to October 2017, 33 rainfall events occurred in the study area (Fig. 3), with a total rainfall amount of 261.10 mm, the maximum rainfall of 41.80 mm and the minimum rainfall of

0.10 mm. Rainfall events of <5 mm in 24 h were the most frequent, accounting for 66.67% of the total rainfall events, but only accounting for 15.01% of the total rainfall amount. The rainfall events of 5–10 mm over 24 h accounted for 9.09% and 8.23% of the total rainfall events and the total rainfall amount, respectively. The rainfall events of 10–25 mm over 24 h accounted for 15.15% and 36.31% of the total rainfall events and the total rainfall amount, respectively. Rainfall events of ≥25 mm over 24 h accounted for 9.09% of the total rainfall events, but accounted for 40.44% of the total rainfall amount. During the experiment, the study area was dominated by small rainfall events, while the occurrence frequency of large rainfall events was very low, but their influence on the total rainfall was high. July and August are concentrated rainfall periods, accounting for 80% of the total rainfall events.

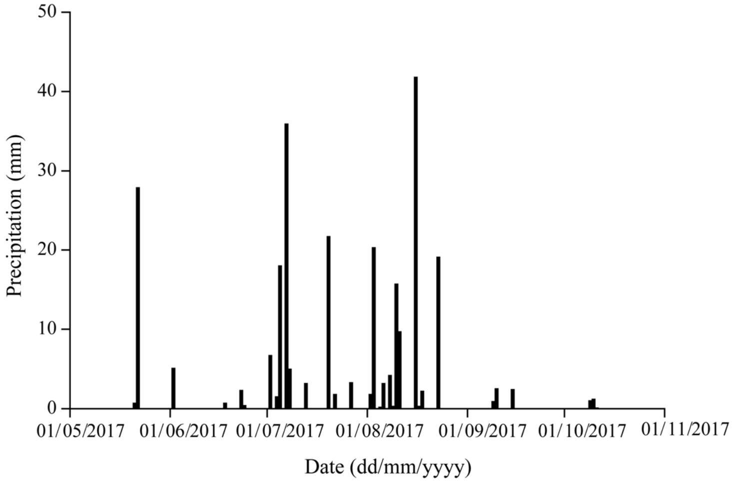

Fig. 3 Precipitation during the observation period in the study area

3.2 Effect of dune vegetation coverage on deep seepage and lateral migration of water

Vegetation coverage had a strong influence on the deep seepage and lateral migration of water in the dunes. The cumulative deep seepage and lateral migration of water in the dunes decreased in the following order: mobile dune>low-coverage semi-fixed dune>high-coverage semi-fixed dune>fixed dune. The cumulative deep seepage water of mobile dunes, semi-fixed dunes (vegetation coverage of 18.03%), semi-fixed dunes (vegetation coverage of 27.12%), and fixed dunes (vegetation coverage of 50.65%) was 147.60, 133.88, 49.55, and 0.69 mm, respectively, and accounted for 56.53%, 51.82%, 18.98%, and 0.26%, respectively, of the rainfall during the observation period. For the same vegetation coverage, the cumulative lateral migration of water was 32.35, 19.87, 16.53, and 5.82 mm, which accounted for 12.39%, 7.61%, 6.33%, and 2.23%, respectively, of the rainfall during the same period (Table 2). The deep seepage and lateral migration of water decreased with the increase in vegetation coverage on the dunes. All of this suggested that the established vegetation reduced the deep seepage and lateral migration of water in the dunes.

3.3 Temporal dynamic characteristics of deep seepage and lateral migration of water in the dunes

The deep seepage and lateral migration of water were mainly collected in July and August, accounting for 96.32% of the total collected water volume (Fig. 4). Deep seepage and lateral migration of water were rarely collected in September and October.

By comparing the occurrence time relationship between deep seepage and rainfall, we found that both deep seepage and rainfall mainly occurred in July and August. There was a close relationship between the rainfall distribution characteristics and the temporal dynamics of deep seepage and lateral migration in the dunes. Spearman correlation analysis was used to obtain the correlation coefficients of monthly cumulative deep seepage and lateral migration of water and

Table 2 Numerical comparison of deep seepage recharge and lateral recharge in dunes

Sand dune type	Vegetation coverage (%)	Slope degree (°)	Deep seepage recharge (D)		Lateral recharge (L)		D+L
			Deep seepage (mm)	Percentage (%)	Lateral migration (mm)	Percentage (%)	Percentage (%)
Fixed dunes	50.65	15	0.69	0.26	5.82	2.23	2.49
Semi-fixed dunes	27.12	18	49.55	18.98	16.53	6.33	25.31
	18.03	18	133.88	51.28	19.87	7.61	58.89
Mobile dunes	<5.00	21	147.60	56.53	32.35	12.39	68.92

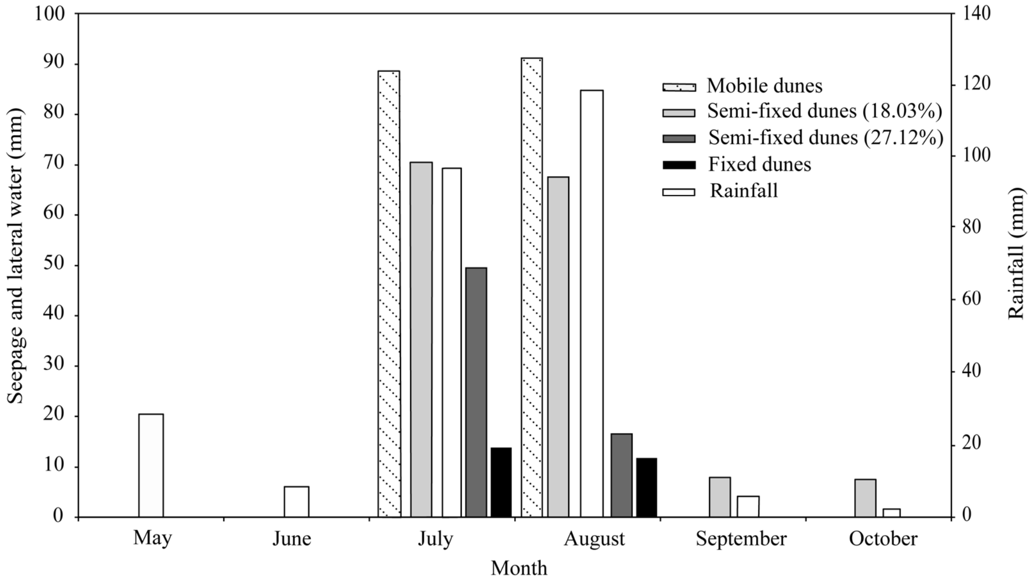

Fig. 4 Temporal dynamics of total seepage and lateral water in sand dunes and rainfall from May to October

monthly rainfall from May to October. The correlation coefficient analysis showed that only deep seepage was correlated with rainfall in some types of sand dunes, but lateral migration showed no correlation in all types of sand dunes. The amount of deep seepage water of the semi-fixed dunes (coverage 18.03%) was significantly correlated with rainfall, while that of mobile dunes was extremely significantly correlated with rainfall (Table 3). This result may be related to the influence of vegetation on the rainfall infiltration process. The lower vegetation coverage of the dunes (such as mobile dunes and semi-fixed dunes with a coverage of 18.03%) is conducive to rainfall infiltration, while a higher vegetation coverage hinders the rainfall infiltration process. In addition, the original soil moisture content also affected the soil water deep seepage process. In months with less rainfall (May, June, September, and October), the limited rainfall is used to replenish the dry soil, and there is no additional water supply for deep seepage.

3.4 Direction and position of the dune slope influenced soil water deep seepage and lateral migration process

During the observation period, the cumulative deep seepage and lateral migration of water varied with the dune slope directions and positions (Fig. 5).

The different directions of the dune slope affected the soil water deep seepage and lateral migration process. The amounts of deep seepage and lateral migration of water on the windward slope were lower than those on the leeward slope. The average deep seepage was 55.07 mm on the windward slope and 67.30 mm on the leeward slope. The average lateral migration of water was 24.16 mm on the windward slope and 51.95 mm on the leeward slope. The different positions on the dune slope also affected the soil water deep seepage and lateral migration process. The

Table 3 Correlation analysis between rainfall and seepage water in sand dunes

Sand dune type	Seepage type	Correlation index
Fixed dunes (50.65%)	Lateral migration	0.27
	Deep seepage	0.39
Semi-fixed dunes (27.12%)	Lateral migration	0.27
	Deep seepage	0.53
Semi-fixed dunes (18.03%)	Lateral migration	0.37
	Deep seepage	0.82*
Mobile dunes (<5%)	Lateral migration	0.64
	Deep seepage	0.94**

Note: * indicates significance at $P<0.05$ level, and ** indicates significance at $P<0.01$ level.

amount of deep seepage and lateral migration of water showed a decreasing trend from the bottom to the middle and to the top of the dune slope. The average deep seepage water at the bottom, middle, and top of dune slope was 76.79, 45.58, and 25.13 mm, respectively. The average lateral migration of water at the bottom and middle of dune slope was 41.19 and 34.92 mm, respectively.

In the same direction and position of the dune slopes, the deep seepage and lateral migration of water showed an increasing trend with the decrease of the vegetation coverage. On the windward slope, the fixed dune had the lowest deep seepage and lateral migration of water, while the mobile dune had the highest. The difference in deep seepage and lateral migration of water between the two dunes was 83.89 and 34.42 mm, respectively. On the leeward slope, the difference in deep seepage and lateral migration of water between fixed dunes and mobile dunes was 103.06 and 80.73 mm, respectively. On the same position of the dune slope, the fixed dune had the lowest deep seepage and lateral migration of water, while the mobile dune had the highest. At the bottom, middle, and top of the slope of the dunes, the difference in the deep seepage water between the two dunes was 117.54, 69.42, and 44.13 mm, respectively.

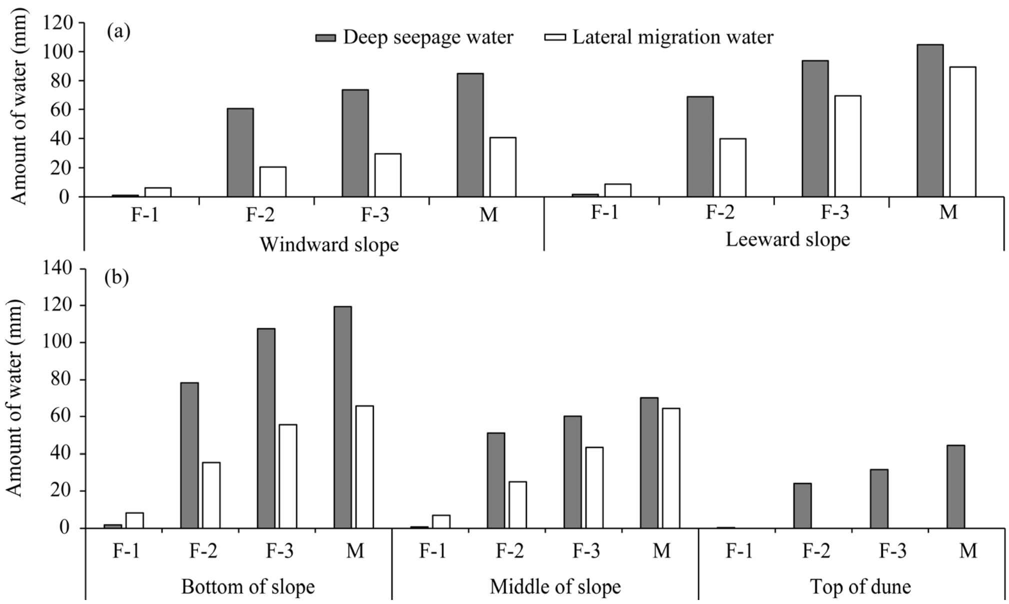

Fig. 5 Cumulative deep seepage and lateral migration of water on different slope directions (a) and positions of the dunes (b). F-1, fixed dunes with 50.65% vegetation coverage; F-2, semi-fixed dunes with 27.12% vegetation coverage; F-3, semi-fixed dunes with 18.03% vegetation coverage; M, mobile sand dunes.

3.5 Estimation of suitable retention mobile dunes in dune ecosystems

The land types of the Horqin Sandy Land usually include two types, namely, dune and inter-dune lowland, and typically, the area ratio of inter-dune and dune is 1:2. Dunes can be divided into mobile dunes and fixed dunes according to vegetation coverage. To maintain the water balance of

artificial fixed dune ecosystems, it is necessary to ensure the balance between the water supply quantity of the dune and the water consumption of the inter-dune. We retained the proportion of the mobile dune area by the following calculation method: Suppose the study area is 100.00 units, the area of inter-dune lowland would be 33.30 units, and the dune area would be 66.60 units according to the area ratio of inter-dune and dune (1:2) in the Horqin Sandy Land. Then, we divided the dune area into a mobile dune area (L) and a fixed dune area (G), and L+G=66.60 units.

According to the results of this study, the deep seepage and lateral migration of water in mobile dunes and fixed dunes accounted for 68.92% and 2.49%, respectively, of rainfall in the same period. From the results of previous studies on the water balance of inter-dune lowland, we deduced that the evapotranspiration of the inter-dune lowland exceeded 23.25% of the rainfall in the same period (Yuan et al., 2008; Liu et al., 2009). According to the water balance of the dune ecosystem, the amount of water supplied by the dunes should be equal to the amount of water consumed by the inter-dune lowland. Then, L×68.92%+G×2.49%=33.30×23.25% (L=9.16 and G=57.44). The proportion of the retained area of mobile dunes in the dune area is calculated as mobile dune area/sand dune area=9.16/66.60=0.1375. This showed that the proportion of the retained area of mobile dunes in the dune area should be kept above 13.75% to maintain the overall water balance within the region. Considering the water balance and sand control effects, the appropriate proportion of the retained area of mobile dunes should be >13.75% in the sand dune area. The practical significance of the research results is as follows: in the construction of sand fixation projects, in order to maintain the water balance of the dune ecosystem, it is not possible to build all dunes as fixed dunes, and at least 13.75% of the dune area should be retained as mobile dunes. This study only put forward the proportion of area to be retained by mobile dunes in terms of quantity, but the spatial distribution of retained mobile dunes in the dune ecosystem also affects the water balance process, which needs to be further studied.

4 Discussion

Deep seepage is closely related to vegetation coverage, rainfall, and soil physical properties. Previous studies found that vegetation affected the water deep seepage process by canopy rainfall interception, surface litter interception, and root water absorption (Yang et al., 2014; Song et al., 2020). With the increase in the vegetation coverage and the increase in plant age, the amount of deep seepage water would decrease. Allison et al. (1990) showed that the amount of deep seepage water increased by two orders of magnitude in the Murray Basin in Australia after native vegetation removal compared with that without vegetation removal. Feng et al. (2015) conducted a study on the amount of rainfall seepage below 200 cm in mobile dunes in six deserts in China and also found that the vegetation coverage had a great influence on the amount of deep seepage water. When the vegetation coverage exceeded 45%, the deep seepage water of the dune did not exceed 2% of the rainfall in the same period. In the current study, we also confirmed that vegetation affected the soil water deep seepage process. With the increase in vegetation coverage, the amount of deep seepage water decreased in the dunes. Deep seepage in high vegetation coverage fixed dunes (50.65% of coverage) only accounted for 0.26% of the rainfall in the same period, which is consistent with previous research conclusions.

In addition to the effects of vegetation coverage, rainfall is the main factor that affected the amount of deep seepage water. Within 120 h after rainfall of 22.00 mm in the Horqin Sandy Land, the depth of rainfall infiltration in mobile dunes increased by 50–80 cm compared with that in an artificial *Caragana microflora* Lam. shrub region (Alamusa et al., 2004). Li et al. (2015) showed that when the soil water content was kept within the range of field water capacity, rainfall and rainfall intensity were the main factors that affected the deep seepage water, and there was a significant positive correlation between rainfall and the deep seepage water. Liu et al. (2006) showed that in the southeast of the Horqin Sandy Land, rainfall less than 13.40 mm would evaporate before reaching the groundwater; thus, it was considered invalid rainfall, and only

rainfall greater than 13.40 mm was considered able to recharge groundwater. Yuan et al. (2008) showed that rainfall greater than 15.00 mm could replenish deep soil water in the Mu Us Sandy Land in China. Yang et al. (2014) suggested that heavy precipitation greater than 25.00 mm could replenish deep soil water in shifting sandy land in arid and semi-arid regions. Kees et al. (2005) showed that the deep seepage water in humid areas was larger than that in arid areas. Liu et al. (2011) studied the relationship between seepage and rainfall, and found that increasing the amount of rainfall would increase the amount of seepage recharge water. In this study, we found that the amount of deep seepage water and occurrence time were highly consistent with rainfall events. However, vegetation coverage affected this correlation, and higher vegetation coverage would reduce the degree of the correlation. We found that the significant correlation between seepage water and rainfall occurred only when the dune vegetation coverage was low.

Soil physical properties also affect the water deep seepage process. Guo et al. (2005) studied the deep seepage in three kinds of soils in the northern piedmont plain of the Tianshan Mountains for groundwater recharge, and found that coarse-grained soil was more conducive to water seepage and recharge than fine-grained soil. Wang et al. (2008) found that soil with higher gravel content, loose soil texture, and higher porosity favors infiltration of water into deep layers. Cook and Kilty (1992) also showed that the deep seepage of water in coarse soil was larger than that of water in fine soil. In this study, the soil structure characteristics of the sand dunes were conducive to the water infiltration process. The soil structure of the dune was mainly composed of 0.05–0.25 mm sand grains, accounting for more than 60% of its composition, followed by 0.25–1.00 mm sand grains, accounting for more than 25% of its composition. The soil structure of the dune determines its high water infiltration rate. The initial infiltration rate was 12.02 mm/min, and the stable infiltration rate was 3.49 mm/min (Yin et al., 2022). Due to the influence of the soil structural characteristics of the dunes, the process of rainfall infiltration was more rapid on the dunes, and the effect of vegetation on this process was more obvious.

A reasonable area between mobile dunes and fixed dunes can maintain the water balance in an artificial fixed dune ecosystem by maintaining sufficient deep water seepage recharge. During the construction of conventional desertification control projects by artificial vegetation, all mobile dunes were usually transformed into fixed dunes by planting sand-fixing plants in order to enhance the controlling effect. Although this method had a good controlling effect, the establishment of sand-fixing vegetation would reduce the hydrological regulation function of mobile dunes, change the water balance of fixed dune artificial ecosystems, and cause a water imbalance, which could lead to reduced stability of artificial ecosystems in fixed dunes. So far, no quantitative results have been proposed on this issue. To address this issue, we derived the appropriate area ratio of mobile dunes and fixed dunes in an artificial fixed dune ecosystem based on our results. The proportion of the retained area of mobile dunes in the dune area should remain higher than 13.75% to benefit the water balance of the sand dune area. The result may not be precise, but it could provide a new research approach in artificial sand-fixing vegetation establishment, proposing a range of values of the proportion of retained area of mobile dunes. This study provides an important reference for future research.

5 Conclusions

The vegetation coverage affected the deep seepage and lateral migration of water in the dunes. With the increase in the vegetation coverage, the deep seepage and lateral migration of water in the dunes gradually decreased. The establishment of sand-fixing vegetation reduced the hydrological adjustment ability of the sand dunes. The direction and position of the dune slope affected the soil water deep seepage and lateral migration process. The amounts of deep seepage and lateral migration of water on the windward slope were lower than those on the leeward slope. The amount of deep seepage and lateral migration of water showed a decreasing trend from the bottom to the middle and to the top of the dune slope. According to the influence of vegetation coverage on the seepage water of mobile dunes and fixed dunes, the proportion of the retained area of mobile dunes in the dune area should remain above 13.75% to maintain the overall water

balance within the region. These findings provide a reliable basis for the accurate assessment of water resources within a sand dune ecosystem and guide the construction of desertification control projects to maintain the water balance.

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